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THERMAL AND CARDIOVASCULAR STRAIN FROM HYPOHYDRATION: INFLUENCE OF EXERCISE INTENSITY

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ABSTRACT

This study determined the effects of exercise intensity on the physiologic (thermal and cardiovascular) strain induced from hypohydration during heat stress. We hypothesized that the added thermal and cardiovascular strain induced by hypohydration would be greater during high intensity than low intensity exercise. Nine heat-acclimated men completed a matrix of nine trials: three exercise intensities, 25%, 45% and 65% $\dot{V}O_2max$; and three hydration levels, euhydration and hypohydration at 3% and 5% body weight loss (BWL). During each trial, subjects attempted 50 min of treadmill exercise in a hot room (30°C db, 50% rh) while body temperatures and cardiac output were measured. Hypohydration was achieved by exercise and fluid restriction the day preceeding the trials. Core temperature increased ($P<0.05$) 0.12°C per %BWL at each hypohydration level and was not affected by exercise intensity. Cardiac output was reduced ($P<0.05$) compared to euhydration levels and was reduced more during high compared to low intensity exercise after 5% BWL. It was concluded that: a) the thermal penalty (core temperature increase) accompanying hypohydration is not altered by exercise intensity; and b) at severe hypohydration levels, the cardiovascular penalty (cardiac output reduction) increases with exercise intensity.

Keywords: dehydration, stroke volume, cardiac output, thermoregulation

INTRODUCTION

Persons performing physical activity while hypohydrated (reduced total body water) have increased physiologic strain (9,19), degraded performance (2,17) and increased susceptibility to heat injury / illness (20). During hot weather, fluid balance is an important issue because the hot climate greatly increases fluid requirements (8), and hypohydration's adverse effects are greater during exercise combined with climatic heat stress than during exercise stress alone (15,18). Most individuals perform prolonged exercise under some level of hypohydration, with some losing up to 6% of their pre-exercise body weight during activity (15,17). Since athletic events and occupational tasks require a range of exercise intensities (from ~25% to > than 100% $\dot{V}O_2max$) it is important to consider whether the exercise intensity (metabolic rate) will modify the adverse effects of hypohydration. While several studies have described the physiologic responses to different hypohydration levels, no study has examined whether exercise intensity modifies the physiologic burden imposed by hypohydration.

The purpose of this study was to determine the effects of exercise intensity on the physiologic (thermal and cardiovascular) strain induced by hypohydration during heat stress. Body temperatures and cardiac output were measured during a matrix of exercise and hydration conditions which will be encountered during athletic events and many occupational tasks. We hypothesized that the added thermal and cardiovascular strain induced by hypohydration would be greater as exercise intensity increased. This hypothesis was based on our observation that hypohydration induced a smaller core temperature increase (above euhydration levels) in studies where volunteers performed low intensity exercise compared to other studies where volunteers performed higher intensity exercise (17).

METHODS

Subjects. Nine healthy heat acclimated men participated in this study. They had a mean±SD age of 24±6 yr, height of 176±8 cm, body weight 80.5±13.7 kg, and maximal oxygen uptake ($\dot{V}O_2max$) of 56.5±6.8 $ml \cdot kg^{-1} \cdot min^{-1}$. All subjects gave their voluntary and informed consent to participate in this experiment which was approved by the appropriate Institutional Review Boards. Other results from this study have been published (10,11).

Experimental Protocol. Prior to experimental testing each subject's $\dot{V}O_2max$ was determined by an incremental treadmill test (21). In addition, during the 2 week period preceding experimental testing, nude body weights were measured daily to establish baseline body weights that represented euhydration for each subject. These body weights were taken in the morning after voiding and prior to breakfast. Additional nude body weights were also taken periodically during testing to adjust for body weight changes over time.

The subjects were heat acclimated by walking (30-40% $\dot{V}O_2max$) for two 50-min exercise bouts separated by 10 min rest in the heat (40°C db, 20% rh or 35°C db, 75% rh) on 10 occasions during a 12 day period. Water was available ad libitum during the exercise sessions. Within 3 days of completing the heat acclimation protocol, the experimental trials were initiated. The subjects then completed 9 experimental trials in random order consisting of 50 min of treadmill exercise in a hot climate (30°C db, 50% rh, wind speed 1 $m \cdot s^{-1}$; WBGT = ~26°C). During each trial the subjects exercised at either 25% (low intensity), 45% (moderate intensity) or 65% (high intensity) of their individual $\dot{V}O_2max$ when hypohydrated by either 0%, 3% or 5% of their baseline body weight. Generally, two tests were performed per week, with a minimum

of one week separating the 5% hypohydration trials. The trial order was varied to minimize any effects of trial order. The trials were terminated if predetermined end-points of heart rate (95% maximum heart rate) or core temperature (39.5°C) were achieved. The subjects wore only shorts, socks and athletic shoes during exercise. Three hundred ml of warm water (37°C) were provided at 20 min of exercise to offset water lost through sweating.

Hypohydration was achieved the day before each trial, using a standardized exercise-heat protocol (11,18-20) in which the volunteers either drank in proportion to the level of hypohydration desired or did not drink to replace sweat losses. All subjects completed the dehydration sessions 12-15 h prior to the experimental tests and spent the night resting in a temperate climate. During the rest and/or sleeping period, food and fluid intake were available if body weight was below the desired level. Fluids were restricted if body weight was not below the desired level. The subjects were instructed to standardize their food and fluid intake during the 48 h period preceding each trial. Upon awakening, subjects were given 200 ml of 100% fruit juice to standardize fluid intake the morning of the experimental test.

Experimental Procedures. Core (esophageal, T_{es}) and skin temperature were recorded at one minute intervals. Skin temperatures were measured at 4 sites (forearm, chest, thigh and calf) and mean weighted skin temperature (T_{sk}) calculated (13). Mean body temperature was calculated using a 9:1 T_{es} to T_{sk} weighting. Average T_{es} was calculated by averaging the respective temperatures measured over the final 20 min of exercise. This time period was chosen as it avoided the rapid rise of core temperature which occurred during the first 20 min of exercise. If a trial was discontinued early, average T_{es} was calculated from 30 min to end of exercise and the same endpoint time was used to calculate average T_{es} and T_b for the other

hydration levels at that exercise intensity.

Oxygen uptake and carbon dioxide production were determined via open circuit spirometry (Model 2900, Sensormedics Corp., Yorba Linda, CA) prior to each measurement of cardiac output. Cardiac output was measured in triplicate, at 3 min intervals after 6 min and 36 min of exercise using a CO_2 rebreathing technique (6). Estimates of CO_2 content were corrected for hemoglobin concentration.

Blood samples were obtained from an indwelling Teflon catheter placed within a superficial forearm vein. Blood samples were obtained at rest following 15 min of quiet standing in the warm environment, at 20 min of exercise and during the final minute of exercise. Hemoglobin concentration was measured in duplicate with a Hemoglobinometer (Coulter Electronics Inc., Hialeah, FL). Plasma osmolality was measured in triplicate by freezing point depression (Precisions Systems Inc., Natick, MA).

Plasma volume and erythrocyte volume were measured on one occasion by the ^{125}I-labeled albumin and the ^{51}Cr methods (21), respectively. Blood volume was calculated as the sum of the plasma volume and erythrocyte volume. Percent changes in blood volume were calculated from hemoglobin and hematocrit (7). The absolute blood and plasma volumes were calculated by adjusting the measured resting blood by the percent changes in hemoglobin and hematocrit.

Statistical Analysis. The independent effect of hydration on physiologic responses at each exercise intensity were analyzed using 2 way repeated measures analysis of variance. The independent effect of exercise intensity on the core temperature responses when euhydrated were analyzed using 2 way repeated measures analysis of variance. The effect of exercise intensity on

the added thermal and cardiovascular strain at each hypohydration level were analyzed using both 1- and 2-way analysis of variance. Statistical significance was tested at the $P < 0.05$ level. Tukey's HSD procedure was used to identify differences between means when statistical significance was achieved. Data are presented in text as mean±sd. Preliminary power analyses (power = 0.8, r=0.8) indicated that 7 subjects should have been sufficient to detect an effect size of 0.2°C.

RESULTS

All subjects completed 50 min of exercise during the low and moderate intensity exercise trials. During the high intensity trials, however, 19 of 27 experiments were stopped prior to 50 min exercise due to attainment of medical endpoint criteria for heart rate (95% HRmax) and/or core temperature (39.5°C) levels. As a result, 9 of 27 experiments lacked cardiac output measurements at 40 min of exercise. Hypohydration did not alter ($P>0.05$)$\dot{V}O_2$, pulmonary ventilation or ventilatory equivalent of oxygen.

Body Weight. Preexercise body weights ($P<0.05$) were 80.5±13.7, 78.2±13.5, and 76.6±13.5 kg for the euhydration and for the 3 and 5% hypohydration trials, respectively, and were similar ($P>0.05$) across all exercise intensity trials. The body weight losses (BWL) were 2.8±0.8 and 4.9±1.1% for the 3 and 5% BWL trials, respectively.

Body Temperature Responses. Resting T_{es} when euhydrated were 36.8±0.2, 36.8±0.4, 36.8±0.3°C for 25%, 45% and 65% $\dot{V}O_2$max trials, respectively. Resting T_{es} after 3% BWL were 36.7±0.3, 36.8±0.3 and 37.0±0.4°C for 25%, 45% and 65% $\dot{V}O_2$max exercise, respectively. Resting T_{es} after 5% BWL were 37.0±0.3, 37.0±0.4 and 37.0±0.4°C for 25%, 45% and 65%

$\dot{V}O_2max$ exercise, respectively.

When euhydrated, T_{es} increased (P<0.05) with exercise intensity (Figure 1a). Hypohydration increased (P<0.05) the T_{es} response to exercise and the magnitude of the T_{es} increment was graded with the hypohydration level (Figure 1b). To examine the effect of exercise intensity on the T_{es} increment accompanying hypohydration, the T_{es} responses were normalized to resting temperature values and the difference in temperature between 3% and 5% BWL relative to 0% BWL trials calculated for each exercise time point. Due to subject attrition during the 65% $\dot{V}O_2max$ trials, statistical comparisons across the3 exercise intensities were limited to the first 30 min of exercise. Two-way analysis of variance (intensity x time) at each hypohydration level demonstrated no difference (P<0.05) in T_{es} increment across exercise intensities. Mean skin temperature averaged 0.6°C higher (P<0.05) than when euhydrated during low intensity exercise at 5% BWL. The T_{sk} responses were similar (P>0.05) across hydration levels during 45% and 65% $\dot{V}O_2max$ exercise. Mean body temperatures increased (P<0.05) with exercise intensity and hypohydration level. The T_b increase above euhydration was within 0.1°C across all exercise intensities for both hypohydration levels.

Cardiovascular Responses. Heart rate increased (P<0.05) with exercise intensity averaging 95±7, 119±6, and 149±9 bpm at 10 min of exercise and 98±7, 125±6, and 167±14 bpm at 40 min of exercise when euhydrated, respectively. Hypohydration increased (P<0.05) heart rate above euhydration levels during moderate and high intensity exercise. Statistical analysis of the effect of exercise intensity on heart rate elevations (above euhydration) revealed that there were differences (P<0.05) between exercise intensities at 3% BWL but the chosen post hoc procedure was unable to discriminate differences amongst the mean values (Figure 2). At 5%

BWL, the heart rate elevations were similar (P>0.05) across all exercise intensities.

Stroke volume averaged 145±29, 136±14, and 131±15 ml at 10 min of exercise and 142±25, 130±11, and 119±18 ml at 40 min of exercise when euhydrated during 25%, 45% and 65% VO_2max trials, respectively. Hypohydration lowered (P<0.05) stroke volume at all exercise intensities. The stroke volume reductions (below euhydration) were not altered (P>0.05) by exercise intensity at either hypohydration level (Figure 2).

Cardiac output increased (P<0.05) with exercise intensity when euhydrated averaging 13.6±2.4, 15.9±1.6, and 19.4±1.8 L/min at 10 min of exercise and 13.7±2.0, 16.1±1.5, and 19.7±2.5 L/min at 40 min of exercise, respectively. Hypohydration reduced (P<0.05) cardiac output during 45% and 65% VO_2max exercise. While hypohydration tended to lower cardiac output during 25% VO_2max exercise the reductions were not statistically significant (P<0.10). The magnitude of cardiac output reductions from euhydration levels increased with exercise intensity (Figure 2) at 5%BWL (P<0.05) but did not achieve statistical significance at 3% BWL (P<0.2).

Blood parameters. Plasma osmolality increased (P<0.05) progressively with hypohydration level (0%=284±5; 3%=289±6; 5%=295±5 mosm/kg) and increased (P<0.05) with exercise intensity. Exercise intensity, however, did not alter (P>0.05) the magnitude of osmolality increase accompanying hypohydration. Blood volume decreased progressively (P<0.05) with hypohydration level (0%=5.17±0.56; 3%=5.04±0.64; 5%=4.96±0.56 L). Exercise intensity did not modify (P>0.05) the magnitude of blood volume decrease associated with hypohydration.

DISCUSSION

This study determined whether the physiologic impact of hypohydration during exercise-heat stress becomes more severe with higher exercise intensity. Previous research had identified heat acclimation state (4,18) and aerobic fitness (4,5) as factors influencing the magnitude of thermal penalty associated with hypohydration during exercise-heat stress. In this study, these factors were controlled by heat acclimating the subjects and using relative exercise intensities. The exercise intensities ranged from 25% to 65% of maximal aerobic power; similar to many athletic and occupational tasks. It is acknowledged that some athletic events require higher relative exercise intensities, however, their use would have resulted in uncompensable heat stress (12) and exhaustion occurring before steady-state physiologic responses could be obtained. We chose to employ a hypohydration approach (fluid loss prior to exercise) rather than a progressive dehydration approach, to avoid the confounding influences of exercise time and changing hydration levels. By controlling the method of water loss, the magnitude of water loss (i.e., similar body weight loss, hypertonicity, hypovolemia), the climatic conditions, and using a repeated measures study design, we were able to directly assess the effects of exercise intensity on the physiologic penalty induced by hypohydration during heat stress.

We found that exercise intensity had little effect on the thermal penalty (core temperature elevation) associated with hypohydration. The three exercise intensities produced similar T_{es} increments after both 3% and 5%BWL. Although there was a tendency for a smaller thermal penalty after 5% BWL when performing low intensity exercise, the magnitude of the difference did not achieve statistical significance. Furthermore, when differences in mean skin temperature between trials were accounted for by calculation of mean body temperature, the thermal

responses to 5% BWL became more similar, supporting the conclusion that the low exercise intensity had little impact on the thermal penalty accompanying hypohydration. At 3% and 5% BWL, core temperature increased by 0.12°C per %BWL across the three exercise intensities. These hypohydration mediated core temperature elevations are comparable to other published values (19,23).

The cardiovascular (cardiac output reduction) penalty imposed by hypohydration generally became larger as exercise intensity increased, particularly at high levels of fluid loss. This finding suggests that hypohydrated athletes performing high intensity exercise might be at greater risk for physical performance degradation than those performing low intensity exercise in the heat. The rationale for this statement is that during high intensity exercise, a-$\bar{v}O_2$ differences are close to maximum so any cardiac output reduction will make it difficult to maintain the required oxygen uptake (3). Sawka and colleagues (16) demonstrated this in hypohydrated runners during high intensity prolonged exercise. They showed that cardiac output declined over time and that a-$\bar{v}O_2$ difference widened to maximum values at the point subjects were unable to maintain pace. During lower intensity exercise, even if hypohydration causes a cardiac output reduction, the a-$\bar{v}O_2$ difference can widen to achieve the oxygen uptake required to maintain performance.

The magnitude and pattern of cardiovascular responses observed in this study agree with those previously reported for hypohydrated subjects during exercise (1,14,22). Only Saltin (14), however, had previously examined the influence of exercise intensity in hypohydrated subjects. That study was not performed in the heat and lacked sufficient numbers of subjects to statistically evaluate the data. Examination of the individual data, however, suggests that stroke

volume declined and heart rate increased similarly whether exercising at 45% or 77% $\dot{V}O_2max$ when hypohydrated.

One potentially confounding factor in this study was the use of the same wind velocity at each exercise intensity. The wind speed used (0.9 m/sec) was insufficient to prevent thermal and cardiovascular drift during the high exercise intensity, and 18 of the 27 trials at 65% $\dot{V}O_2max$ were terminated due to achievement of 95% maximal heart rate. To determine whether this thermal and cardiovascular drift reduced the magnitude of body temperature and heart rate increase attributable to hypohydration, three of the subjects repeated the high intensity exercise when euhydrated and after 5% BWL when wind velocity was increased to 2.5-3.0 m/sec. Despite attenuating thermal and cardiovascular drift, the core temperature and heart rate increase (T_{es}=0.12°C / %BWL; heart rate=3 beats / %BWL) attributable to hypohydration were similar to the values obtained at the low wind speed. Therefore, it is unlikely that the low wind speed biased our results.

This study determined the effects of exercise intensity on physiologic (thermal and cardiovascular) strain induced by hypohydration during heat stress. We found that the exercise intensity had no effect on the thermal penalty imposed by hypohydration, but high intensity exercise was associated with a greater cardiovascular penalty after 5%BWL. These results indicate that in hot climates, hypohydration might degrade physical performance more during physical activities requiring high intensity than low intensity exercise thus further emphasizing the need for maintenance of body hydration with intensive exercise.

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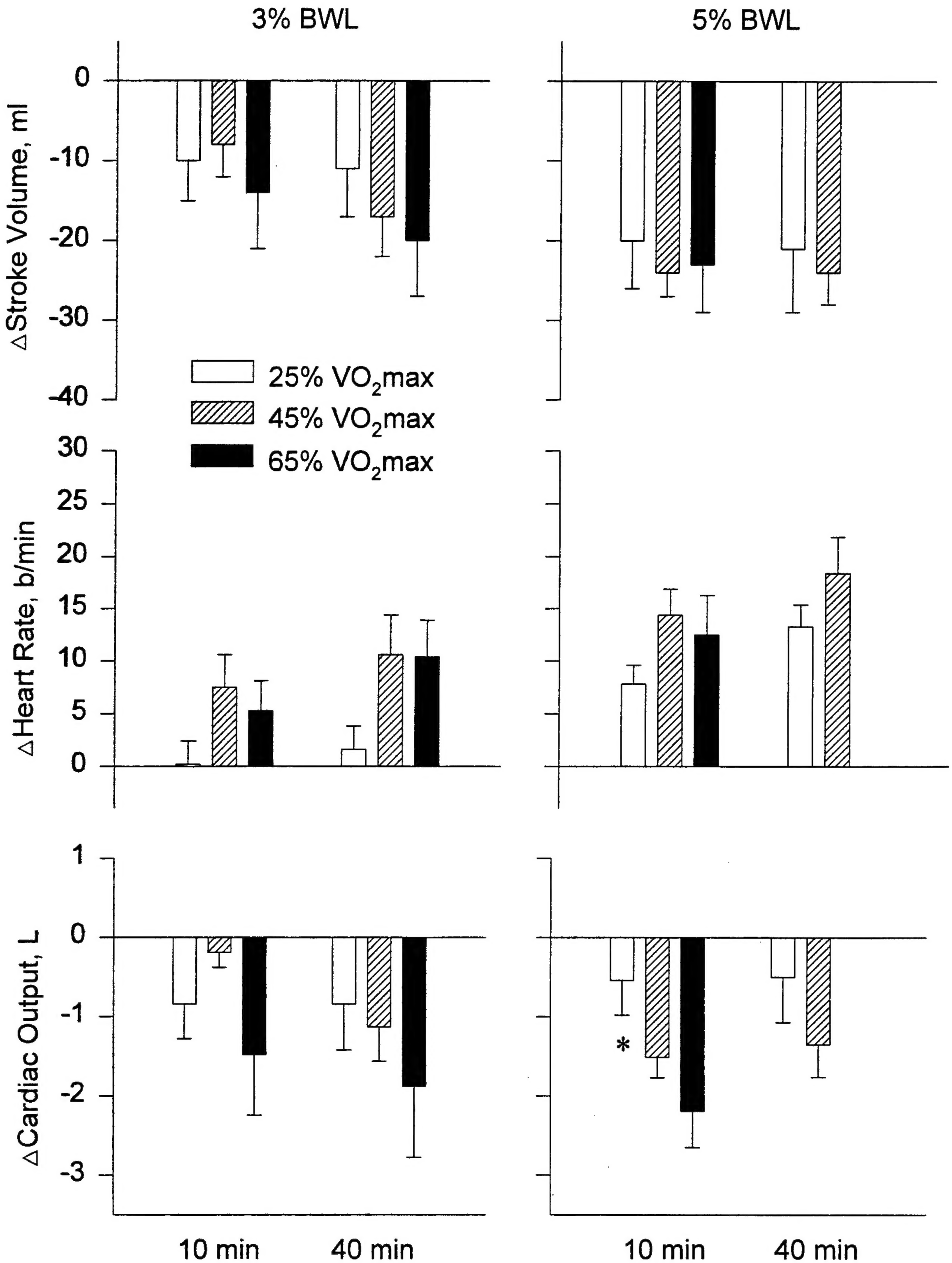
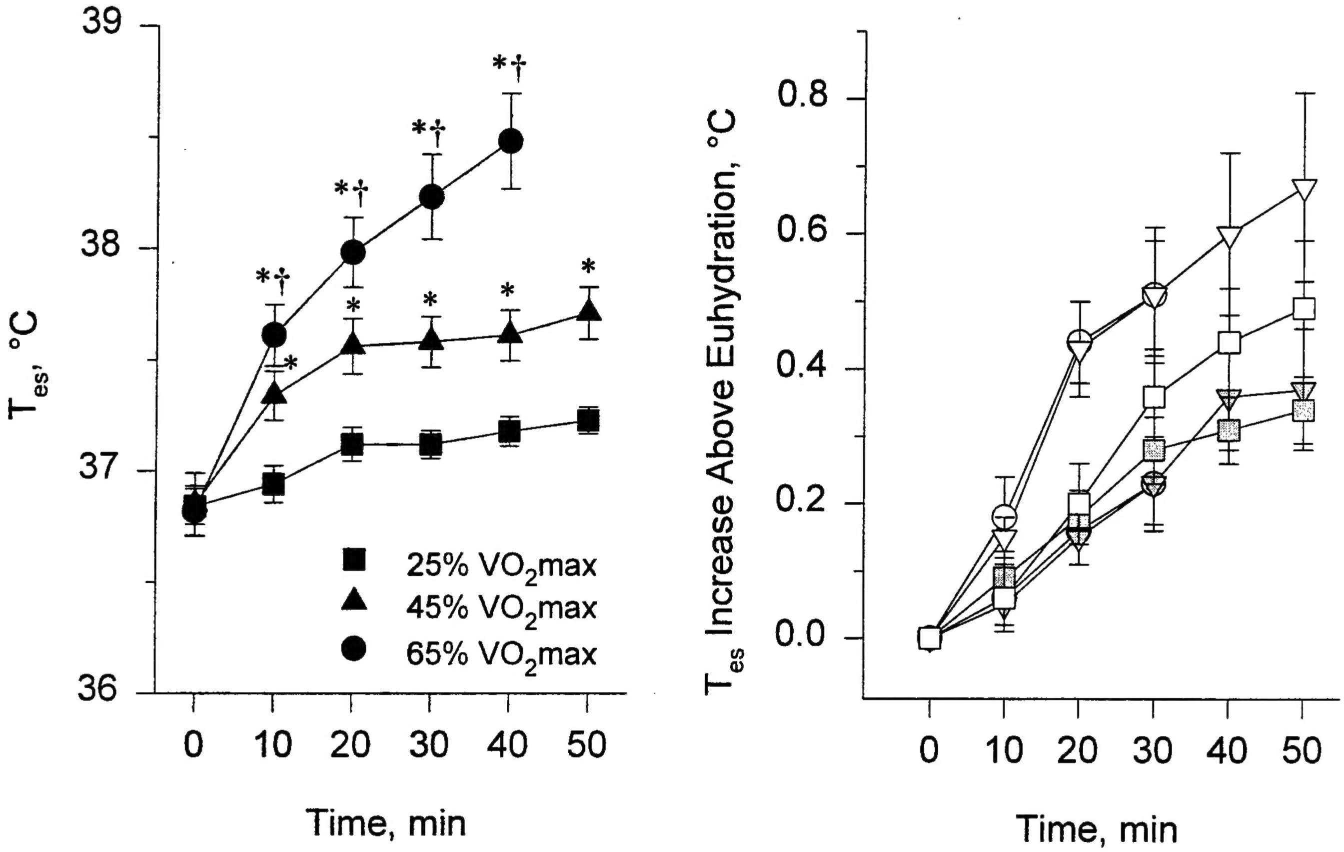
FIGURE LEGENDS

Figure 1. Left plot - Esophageal temperature (T_{es}) responses during exercise at 25%, 45% and 65% $\dot{V}O_2$max when euhydrated (0% BWL). Right plot - T_{es} increment accompanying 3% BWL (shaded symbols) and 5% BWL (open symbols) when exercising at 25%, 45% and 65% $\dot{V}O_2$max. The T_{es} increment accompanying 5% BWL was greater ($P<0.05$) than 3% BWL. Data are means±se for nine subjects except n=8 subjects at 30 min exercise during 65%$\dot{V}O_2$max trials after 3% and 5% BWL. * Greater than 25% $\dot{V}O_2$max. † Greater than 45% $\dot{V}O_2$max.

Figure 2. Cardiovascular changes due to hypohydration (3% & 5% BWL) during low, moderate and high intensity exercise. Data are means±se for 9 subjects for heart rate and 8 subjects for cardiac output and stroke volume with exception that n=6 at 40 min during 65% $\dot{V}O_2$max trial with 3% BWL. * Different than 65%$\dot{V}O_2$max.



3% BWL
5% BWL
ΔStroke Volume, ml
0
-10
-20
-30
-40
25% VO2max
45% VO2max
65% VO2max
ΔHeart Rate, b/min
30
25
20
15
10
5
0
ΔCardiac Output, L
1
0
-1
-2
-3
*
10 min
40 min
10 min
40 min



39
38
37
36
T_{es}, °C
*†
*
25% VO_2max
45% VO_2max
65% VO_2max
0
10
20
30
40
50
Time, min
0.8
0.6
0.4
0.2
0.0
T_{es} Increase Above Euhydration, °C
0
10
20
30
40
50
Time, min